Integration of a Particle Jamming Tactile Display with a Cable-Driven Parallel Robot

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Abstract. Integration of a tactile display onto the end effector of a robot allows free-hand exploration of an encountered-type environment that provides both kinesthetic and cutaneous feedback. A novel tactile display approach, called Haptic Jamming, uses a combination of particle jamming and pneumatics to control the stiffness and shape of a surface. The tactile display mounts to the cable-driven platform of a kinesthetic system for medical simulation, called KineSys MedSim. The parallel structure of the robot provides a high strength-to-weight ratio for kinesthetic feedback in combination with a spatially aligned visual display. Its controller uses hand tracking to move the platform to the portion of the workspace the user is reaching toward. Data from a lump localization simulation demonstrates that the integrated system successfully tracks the user's hand and reconfigures the tactile display according to the location of the end effector.

Keywords: Haptic device design, haptic I/O, particle jamming, tactile display, parallel cable robotics

1 Introduction

Realistic touch feedback in virtual environments requires both cutaneous tactile feedback and kinesthetic feedback to accurately recreate physical interactions. This involves rendering not only forces but also vibrations, skin deformation, and other tactile sensations. We present a novel medical simulation system that enables simultaneous programmable control of tactile and kinesthetic feedback.

Many medical procedures require a clinician to rely upon the sense of touch to make a diagnosis or treatment decision, so haptic feedback plays an important role in any simulator used to practice these procedures. Classic mannequins provide real physical environments for the trainee to explore directly with his or her hands, but do not permit significant changes in geometry or material properties to simulate a variety of scenarios. On the other end of the spectrum of haptic simulation, virtual environments can be reprogrammed to render a wide range of medical scenarios, from the contour of a skull to the compliance of a soft tissue.

Typically, virtual environments that provide haptic feedback apply resolved forces to a hand-held stylus, thimble, or other handle via a series of motors for the kinesthetic feedback. Programmable cutaneous feedback typically requires additional actuators or hardware built into the hand-held component to adjust the vibrotactile, skin deformation, or other cutaneous sensations that the user feels. With this setup, however, the user is constrained to hold onto the end effector of the device at all times and is no longer truly free to explore the physical environment directly with his or her own hands. Even when there is no programmed physical interaction in such a virtual environment, the user still feels the device that he or she is holding.

Bridging the gap between these two ends of the spectrum, tactile displays and shape rendering devices create programmable physical environments with variable shape and mechanical properties for a user to explore directly and freely. The complexity of these tactile displays often results in either a limited size of the explorable workspace or low tactile resolution. In this work, we address these limitations of haptic simulators by integrating a tactile display onto the end effector of a new six degree-of-freedom (DOF) cable-driven parallel robot developed specifically to create virtual environments for medical simulation. The tactile display can adjust both its mechanical and shape properties using particle jamming and pneumatics, as we explain in our previous work [2] [14]. The robot uses eight motors connected to cables on each corner of the end effector to drive the platform in space below a visual display. Integrating these two new devices creates a freely explorable environment with a large workspace and both cutaneous and kinesthetic haptic feedback, a novel combination for medical simulators.

2 Background

In an effort to present users with programmable physical environments they can explore freely, researchers have developed number of tactile displays, shape rendering devices, and encountered-type haptic displays. Many tactile displays focus primarily on adjustable mechanical properties so that the forces and displacements a user feels while exploring a surface can change. For example, this can be accomplished via magnetorheological fluids [8] or electrorheological fluids [15], which adjust the stiffness or damping of the material with the application of a magnetic or electrical field, respectively. Other tactile displays focus on adjustable shape output properties. Implementations of displays with controllable geometries include shape memory alloy arrays [16] and other various arrays of pins [4] [12] or balloons [6]. The concept of “Digital Clay” [13] represents an ideal for a tactile interface capable of both controllable geometry and stiffness for a deformable computer input and output, and recent displays using particle jamming [14] and pneumatics [3] aim to achieve these features.

The end effector of a 6-DOF robot can create a workspace larger than the typical tactile display, so many encountered-type haptic displays utilize this feature to allow users to explore environments more freely. Using computer vision to track a user’s hand motion allows a robot to relocate a surface mounted to its end effector anywhere within its workspace to simulate a much larger surface

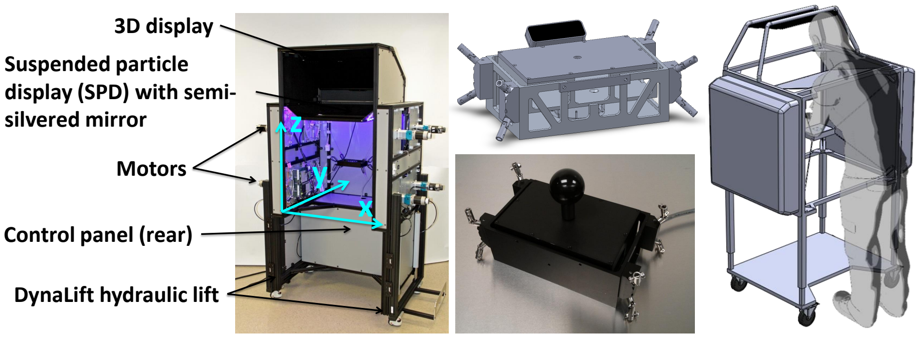

Fig. 1. Photos and CAD drawings of the Kinesys Medsim robot, its coordinate frame, and its end effector. The end effector configuration shown does not have a tactile display integrated but rather a handle for only kinesthetic haptic interaction.

with varying orientations [17]. Other shape rendering interfaces [7] have suggested mounting the display to a robot end effector to present different objects of varying shapes in different regions of the workspace.

Parallel robots, in contrast to serial manipulators, connect the end effector directly to the base through multiple links [10]. In cable-driven parallel robots where the end effector is suspended below the base and cable mass is minimal, the manipulator can be viewed as an upside-down version of the common Stewart-Gough platforms, which allows the calculation of their inverse kinematics in six degrees of freedom [11]. However, the cables can only support tensile forces and not compressive forces [1]. Parallel cable robots typically have a larger workspace and lower weight than serial robots of similar size and strength, features that have driven their use in applications ranging from shipping to neurorehabilitation [9].

3 KineSys MedSim Robot

The second generation of a kinesthetic system for medical simulation (KineSys MedSim), shown in Figure 1, creates a hands-free haptic environment by moving a tactile display in three-dimensional space underneath a visual display of a virtual environment. The first generation of the KineSys MedSim robot is described in [5]. A user stands next to the robot and looks down at the reflection of a 3D display above his or her head on the semi-silvered mirror of a suspended particle device (SPD) that changes light transmission properties under the application of a voltage. Switches on the right side allow adjustment of the transparency of the SPD display and of the robot height via a hydraulic lift. Thus, the visual display can sit just below the chin of anyone within the 10th percentile of female height to 90th percentile of male height and can range from fully mirroring the screen above to allowing some visibility of the user's hand below.

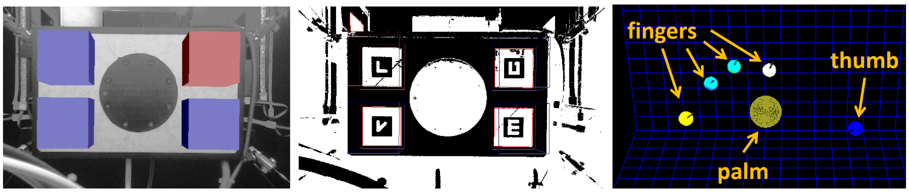

Fig. 2. A video camera below the workspace is used in combination with the AR Tracking toolkit and fiducial markers on the bottom of the end effector to set the home position of the robot. A Leap Motion sensor tracks the user's fingers and palm (right).

Beneath the visual display, eight cables drive the end effector platform around a 0.86 m×0.76 m×0.71 m workspace. The corners of the workspace each house a fairlead and a pulley to guide the cables around the shafts of eight brushless DC motors that extrude out of the sides of the robot with encoders for position tracking. The robot can generate up to 178 N of force with a maximum velocity and acceleration of 0.762 m/sec and 2.54 m/sec^2, respectively. As shown in Figure 1, the end effector consists of a 0.22 m×0.13 m×0.075 m shell that holds a 0.19 m×0.12 m×0.043 m mounting frame on top of a 6-DOF ATI Gamma NET force-torque sensor. A Beckhoff Automation CX1030-0110 embedded PC serves as the central control unit for the Advanced Motion Controls EtherCAT drives that run the motors. The embedded PC enables a fixed 1000 Hz control loop rate as it communicates with the main GUI client PC. A Leap Motion controller mounts to the outside of the end effector to track the user's hand above the surface and a Logitech HD Webcam mounted below the workspace uses AR Tracking toolkit with the fiducial markers on the bottom of the end effector (Figure 2) to automatically move the end effector to its home position and calibrate the motor encoders when the robot is first powered.

4 Haptic Jamming Display

The Haptic Jamming display provides simultaneous control of shape output and mechanical stiffness in a single interface. The underlying design concept, described in much greater detail in [14], relies on pneumatics and particle jamming. For integration with the KineSys MedSim robot described here, we use a single-cell version of the display, although we have prototyped several multi-cell arrays capable of creating more complex geometries [14].

Particle jamming allows an object to adjust its mechanical properties, typically by filling a flexible membrane with a granular material and applying varying levels of vacuum. In this particular application, we use a hollow silicone membrane with a 0.17 m×0.10 m×0.011 m internal volume filled with coffee grounds such that the grounds jam together and become rigid when the air is vacuumed from the inside of the silicone. We construct the silicone shell by gluing together two separate pieces, both cast from custom laser-cut molds. The bottom piece of silicone is a 3.2 millimeter thick layer that spans the top surface of the mounting

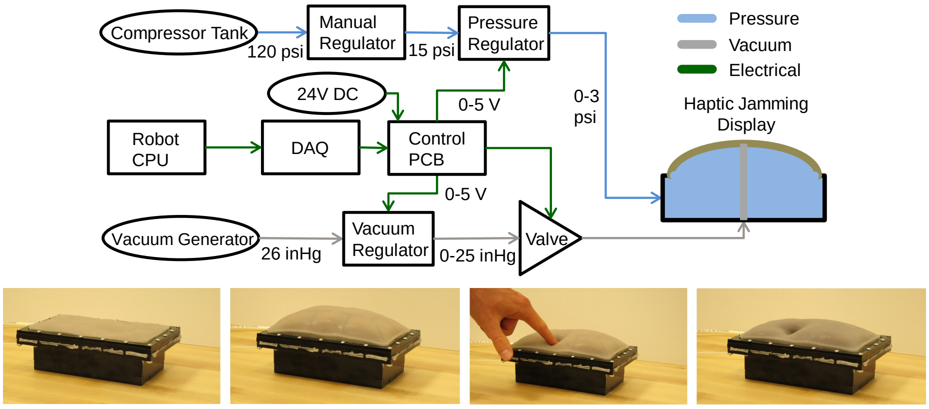

Fig. 3. The system architecture to control a single-cell Haptic Jamming display (top). The tactile display (bottom) consists of a thin particle jamming layer to adjust the stiffness of the surface laid over a pressurized air chamber to adjust its shape.

frame on the end effector of the KineSys MedSim robot with a nub that the vacuum line glues into. The top piece of silicone consists of a .013 meter thick hollow shell that fills with coffee grounds with an internal silicone structure of thin, disconnected walls that help prevent the grounds from shifting around too much when the cell deforms. Without these internal walls, the granules would all shift towards the outside of the cell when it balloons outwards with an increase in air pressure beneath the cell, making the center of the lump less rigid with the application of vacuum to the inside of the cell. This top shell spans the bottom silicone except for a 0.013 meter border on each side that allows a piece of acrylic to clamp the bottom silicone piece onto the edges of a pressure-regulated air chamber below. The air chamber sits inside the mounting frame of the end effector.

A Proportion Air QB3 pressure regulator controlled by a National Instruments X-Series DAQ sets the air pressure inside the chamber. Increasing the pressure in the air chamber while the surface is in its soft, non-vacuumed state balloons the silicone outward. Subsequently applying a vacuum to jam the cell allows it to hold a deformed state rigidly, as depicted in Figure 3.

5 Integration of the Tactile Interface and Robot

We designed the single-cell version of the Haptic Jamming display in Section 4 to fit the dimensions of the end effector, in order to simplify mechanical integration with the KineSys MedSim robot and allow easy interchanging with alternate tactile displays or a handle for purely kinesthetic interaction. Four screws at the corners of the display hold it onto the mounting frame of the end effector such that the force-torque sensor below can register all interaction forces with the display. The pneumatic and vacuum lines feed into the control panel at the back of the robot and run from the electronic regulators and valves on the recessed

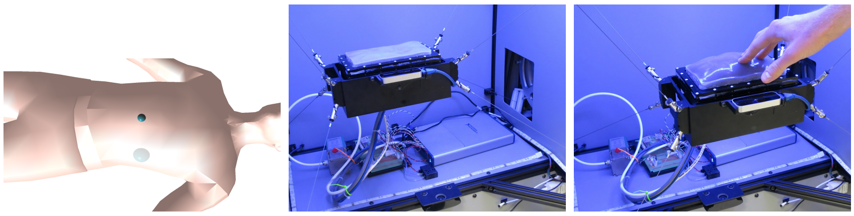

Fig. 4. A single-cell Haptic Jamming display integrated onto the end effector of the KineSys MedSim robot. The graphics show a human torso with a lump location and a green cursor for the end effector position. The tactile display changes from a soft, flat surface to a rigid lump when the cursor aligns with the virtual lump.

panel of the workspace up to the end effector alongside the cables for the Leap controller and the force-torque sensor.

The robot can command a desired lump size and stiffness to the Haptic Jamming display and it will subsequently follow the sequence of timed steps necessary to create that configuration. The display controller updates the robot with a binary state of either reconfiguring or configured. For a preliminary demonstration based on the integrated system's original intent for medical simulation, the graphics use CHAI 3D to show a human torso with a faint sphere to mark the location of an embedded lump, as well as a green cursor that tracks the position of the end effector.

The system switches between two modes during operation. When the user is moving his or her hand freely above the display, the Leap controller tracks the hand position and moves the end effector in a plane below to track the measured X-Y position of the palm, which provides more reliable readings than the individual fingers, and aligns it with the front of the tactile display. If the end effector position aligns with the sphere indicating the embedded lump on the screen, the tactile display reconfigures from a flat, soft surface to a rigid lump, as shown in Figure 4. When the user reaches down to touch the surface, as registered by the force-torque sensor under the tactile display, the system switches into an interactive mode, locking the configuration of the tactile display and using to an impedance controller to render kinesthetic interaction forces from the current position. Figure 5 shows a set of data collected during a sample interaction with the integrated system to demonstrate its functionality. When the end effector's X and Y coordinates fall within 0.013 meters of the lump's coordinates, the soft, flat surface of the Haptic Jamming display converts to a rigid lump by commanding a higher pressure to the chamber beneath the surface to balloon it outward followed by commanding a higher vacuum to the interior of the cell to jam it into its rigid state.

6 Conclusions and Future Work

This paper presents a novel framework for an encountered-type haptic display. The Haptic Jamming tactile display provides both controllable stiffness and

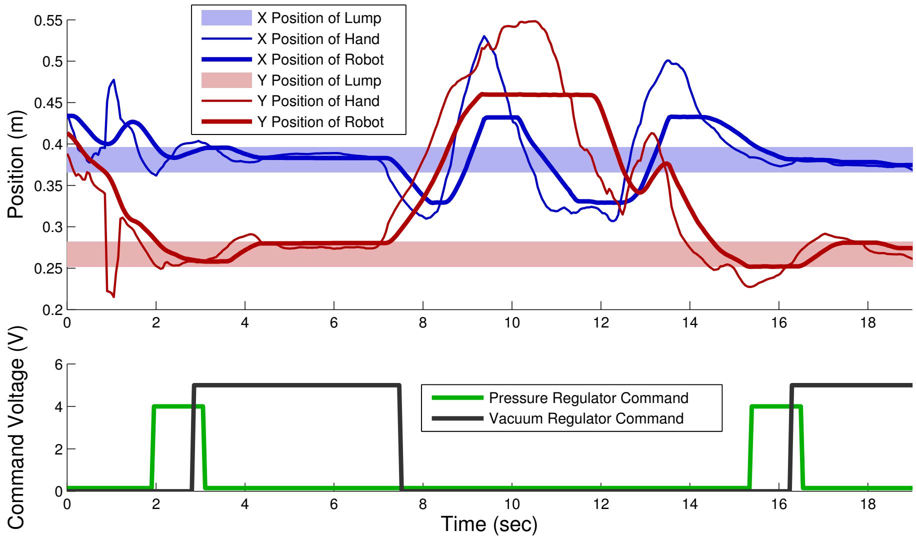

Fig. 5. Data showing the robot end effector tracking the hand as measured by the Leap controller, plateauing at the edge of its workspace. When the end effector reaches the location of the virtual lump, a sequence of commands to the pressure and vacuum regulators convert the Haptic Jamming display from a soft, flat surface to a rigid lump.

shape in an environment that the user can explore directly with his or her hands. The KineSys MedSim cable-driven parallel robot not only provides more physical support for a tactile display than a serial robot, but also allows the platform to add underlying kinesthetic haptic feedback to the cutaneous feedback of the tactile display. A lump localization simulation demonstrates the integration of the graphics, hand tracking, and kinesthetic and cutaneous interaction in a medical simulation scenario. Future work will integrate a multi-cell Haptic Jamming display into the robot to present more complex surfaces, improve the control of the KineSys MedSim robot to utilize all six of its degrees of freedom, and test users in order to explore various control strategies for moving an encountered-type display during haptic interaction. Furthermore, experiments will test the relationship between the controllable kinesthetic stiffness of the robot and the adjustable stiffness of the tactile display and how users perceive these overlapping sensations.

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